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Assessing the Benefits and Costs of Motion for C-17 Flight Simulators

J. R. Gebman, W. L. Stanley, A. A. Barbour,
R. T. Berg, J. L. Birkler, M. G. Chaloupka,
B. F. Goeller, L. M. Jamison, R. J. Kaplan,
T. F. Kirkwood
With C. L. Batten

June 1986

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This study examines the benefits and costs of incorporating a motion system in the C-17 flight training simulator and suggests a standard framework for assessing simulator fidelity requirements in general, and motion cueing alternatives in particular. Using a framework detailed in this report, the research assesses three simulator alternatives: a system having no motion, a system using hydraulic/pneumatic g-seats, and a system using a six-degree-of-freedom (dof) motion platform. The incremental costs of simulators using six-dof motion platforms appear warranted when measured against the likely benefits from their use, if the Air Force devises an adequate training syllabus for C-17 simulators and if the program plan ensures that adequate performance data are collected during flight testing to support simulator software development. Simulators with no motion systems, or those using g-seats, do not appear cost-effective for the C-17 training application. (See also N-2301-AF.)

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June 1986

A Project AIR FORCE report
prepared for the
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PREFACE

In November 1984, the United States Air Force Deputy Chief of Staff for Research, Development, and Acquisition, Lieutenant General Robert Russ,[1] asked The Rand Corporation to perform a quick assessment that would assist the Air Force in evaluating the benefits and costs of incorporating motion systems in C-17 transport aircraft flight simulators, and in developing a general framework for assessing simulator fidelity requirements. Results of this assessment were briefed to Air Force leadership early in the spring of 1985.

This volume documents the major findings of this research project. Technical appendixes that support these findings may be found in *Assessing the Benefits and Costs of Motion for C-17 Flight Simulators: Technical Appendixes*, by J. R. Gebman, W. L. Stanley, A. A. Barbour, R. T. Berg, J. L. Birkler, M. G. Chaloupka, B. F. Goeller, L. M. Jamison, R. J. Kaplan, and T. F. Kirkwood, with C. L. Batten, The Rand Corporation, N-2301-AF, June 1986. These technical appendixes describe experiments to determine the value of motion in training simulators; aircraft features that will influence the C-17's motion; possible effects on motion cues of the C-17's stability and control augmentation system; the fidelity of different simulator motion cueing alternatives; a suggested methodology for assessing the training capability of simulators; the effects of simulator motion on simulator training capability, safety, and avoiding simulator sickness; and the costs of providing motion in simulators.

This research was conducted as a direct assistance activity by the Project AIR FORCE Resource Management Program.

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[1]Lieutenant General Russ was subsequently promoted to General and is now Commander, Tactical Air Command.

SUMMARY

The U.S. Air Force expects to place great reliance on flight simulators for training C-17 transport aircraft aircrews. It will do so not only because of the C-17's high crew ratio but also because the C-17's unique strategic and tactical airlift mission responsibilities will limit opportunities to practice the full breadth of its demanding wartime missions in the airplane during peacetime. Hence, the C-17 simulator needs to adequately represent the important types of information, or cues, that its pilots use to control the aircraft, particularly those cues experienced in wartime situations.

Although dramatic increases in the realism of flight simulators over the past 20 years have often been equated with improved training, users—including the Air Force—have now begun to question whether some kinds of realism are superfluous for the flight simulator's training task. Lacking a formal framework for addressing such questions, the Air Force asked The Rand Corporation to suggest a *framework* for assessing simulator motion requirements and to use it to examine the *benefits and costs* of incorporating a motion system in C-17 simulators.

Our assessment shows that **the incremental costs of simulators using six-degree-of-freedom (dof) motion platforms appear warranted when measured against the likely benefits from their use, if the Air Force devises an adequate training syllabus for C-17 simulators and if the program plan ensures that adequate performance data are collected during flight testing to support simulator software development. Simulators with no motion systems, or those using g-seats, do not appear cost-effective for the C-17 training application.**

FRAMEWORK

The suggested framework for assessing simulator motion requirements uses the following steps:

- Screen simulators to identify the ones that perform best for each generic type that has some prospect of filling the training need.
- Assess the benefits of each generic type, including
  - Subjective considerations of crew members and instructors
  - Improvements in safety
  - Avoidance of simulator sickness
  - Increases in simulator training capability

- Assess the potential costs of each generic type, including
  - Fiscal costs
  - Decreases in available simulator time
- Employ a "scorecard method" to compare potential benefits with potential costs for each generic type.

SCREENING ANALYSIS

The screening analysis yielded three alternatives that had some prospect of filling the C-17's training needs:

- A no-motion system
- A system using combined hydraulic/pneumatic g-seats
- A system using a six-degree-of-freedom (dof) motion platform

No-motion systems rely solely on changes in visual displays, flight instruments, and flight control forces to induce sensations of motion. These systems are commonly used in research and engineering development simulators. *G-seats* additionally move the pilot's body through motions of the seat, measured in inches. Commonly used in fighter aircraft simulators, these systems have not yet been used in operational transport aircraft simulators. In moving the entire simulator cockpit, *six-dof motion platforms* perform excursions measured in feet. The six-dof platform is the most commonly used motion system in simulators approved by the Federal Aviation Administration for air carrier training, and is also used in many military transport-class aircraft simulators.

BENEFITS AND COSTS

The motion platform alternative promises the most benefits. It enjoys a large advantage over the other alternatives in terms of the range of tasks it can train, and also enjoys an advantage in terms of safety benefits, subjective considerations such as crew and instructor confidence, and its potential to reduce the risk of simulator sickness. Its only negative features are a very small contribution to unavailability and a $24 million incremental cost associated with the procurement and operation of the motion platforms for eight simulators for 25 years. However, the motion platform alternative would enjoy a cost advantage if the Air Force were to shift training even slightly

from the no-motion or g-seat simulators to the C-17 in an attempt to compensate for the reduced training capability of those simulators.

Subjective Considerations

For a simulator to be most effective as a training tool, aircrews must have confidence that it provides a faithful representation of the cues they encounter in the airplane. Air Force transport aircraft aircrews express a strong preference for motion platform simulators. Instructors express a similar preference because they use the movement of the platform in evaluating the performance of aircrews during flight checks. They also express concern about students developing overcontrol habits when using simulators without motion—a tendency that has also been observed in numerous experiments.

Safety

Aircrews can practice many potentially dangerous maneuvers in the motion platform simulator rather than in the aircraft, reducing their exposure to training accidents in the aircraft and preparing them to react properly when emergency situations do occur. The other alternatives have difficulty displaying the critical cues used by aircrews in responding to many transport aircraft malfunctions.

Simulator Sickness

A subset of motion sickness, simulator sickness poses operational problems ranging from compromised training to flight safety. Because the motion platform simulator presents motion cues in a more realistic fashion than the other alternatives, it may provide more insurance against the risks of simulator sickness thought to be caused by sensory conflict.

Simulator Training Capability

Our analysis developed a minimum set of flight tasks that represented a full spectrum of the hundreds of tasks C-17 aircrews will perform under various environmental and combat conditions. The motion platform alternative can train all 163 of these tasks and variations of tasks, whereas the g-seat alternative can train only 57 (35 percent) and the no-motion alternative only 29 (18 percent). The fact that the no-motion and g-seat alternatives lack the ability to display

certain needed cues or must provide them from substitute sources diminishes their potential training capability. For example, inherent design constraints of the g-seat severely limit its ability to represent adequately the rapid roll, lateral, and yaw motions characteristic of many transport aircraft emergency maneuvers.

More than 40 percent of the tasks and variations of tasks cannot be trained at all without the motion platform alternative because the lower-capability simulators cannot display the necessary cues and the tasks are too difficult or too dangerous to train in the airplane.

Fiscal Costs

The 25-year life-cycle costs for eight simulators with motion platforms ($607.1 million) is $24.1 million more than for simulators with no motion and $14.5 million more than for simulators with g-seats.

If the Air Force attempts to compensate for shortcomings in the training capabilities of the no-motion or g-seat simulators by shifting training only slightly from the simulator to the C-17, then the cost of additional training in the aircraft and the opportunity cost of those tasks that cannot be trained at all almost certainly make the motion platform the least expensive alternative.

Availability

Maintenance problems of first-generation motion platforms that decreased simulator time available for training have largely been overcome. Differences in the availability of the motion system alternatives are minor at best.

CONCLUSIONS

The $24 million incremental cost for motion platforms for eight simulators over a 25-year life averages $115,000 for each of the 208 C-17s, or $4600 per aircraft per year. This cost appears warranted when measured against potential improvements in flight safety and warfighting capability that result from the much greater training capability of the motion platform simulator. Moreover, training capability shortcomings of the competing alternatives could lead to opportunity costs and additional aircraft operating costs that easily overshadow the incremental cost of the motion platforms. Finally, the greater cueing capability of the motion platform

alternative provides more protection against unknown risks caused by omitting motion cues during training, especially for young and inexperienced aircrews transitioning to the C-17.

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The authors also acknowledge the guidance and assistance provided by the research sponsor through General Robert Russ and Lieutenant Colonel Eugene Clayton.

Finally, the authors particularly acknowledge the assistance of Colonel David Nelson and Lieutenant Colonel Ronald Duke at Headquarters Military Airlift Command, and of Rand colleagues P. Perkins, who compiled the bibliography, B. D. Bradley, S. M. Drezner, G. H. Fisher, M. D. Rich, J. A. Thomson, and W. H. Ware, who provided suggestions and comments through the course of this research, and E. D. Harris and S. Resetar, who provided perceptive technical reviews.

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FIGURES

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I. INTRODUCTION

The use of modern flight simulators has grown dramatically during the past fifteen years. Influenced by the increased costs of operating aircraft and by a recognition that simulators contribute to safety and training efficiency, this growth has been accompanied by constant improvements in fidelity to provide more realistic training. For example, flight simulators now have more degrees of freedom in their motion platforms, and their visual displays now have wider fields of view and greater scene content. Depending on the sophistication of a simulator, an air transport pilot can currently satisfy total recurrent training requirements, upgrade from copilot to captain status, move from one airplane to another in the same group, and even receive total initial training and a rating for a new aircraft entirely through use of the simulator—without ever having to use the aircraft for any dedicated training flights.

The increased realism in simulators has usually been equated with improved training, and the lower costs of simulator time versus aircraft time have historically muted debate about the additional costs of increased realism. Now, however, simulation technology—particularly technology associated with visual displays—has progressed to such an extent that users are beginning to question how much fidelity is enough.

Lacking a formal framework for evaluating requirements for various simulator features, the Air Force has on occasion expressed concern that it may be purchasing unneeded features. Most recently, it has raised questions about the need for a motion system in the C-17 transport simulator.

To help answer these questions, the Air Force asked The Rand Corporation to examine the benefits and costs of incorporating a motion system in the C-17 simulator, and to suggest a standard framework for assessing simulator fidelity requirements in general and motion cueing alternatives in particular.

IMPORTANCE OF THE C-17 SIMULATOR

The selection of a simulator having the appropriate fidelity features will be especially important for the C-17 program because the Air Force is expected to place unprecedented reliance on the C-17 simula-

tor for training.[1] Demands for training time—whether in the airplane or the simulator—will be high because current plans call for a crew ratio of 5.0, (five pilots and five copilots for each aircraft).[2] To maintain such a ratio, it is expected that the Air Force will have to train a large incoming population of relatively young and inexperienced crew members. Because of their inexperience, the quality of their training will be highly important, but heavy peacetime military airlift needs and the wide variety of wartime conditions that crews must train for will limit their opportunities for practicing demanding wartime missions *in the airplane*.

While many aspects of wartime strategic airlift missions are routinely practiced in the conduct of normal peacetime military airlift operations by pilots of C-141 and C-5 transport aircraft, the dual mission role of the C-17 adds to its training burden. According to the *U.S. Air Force Airlift Master Plan* (September 24, 1983), the C-17 will eventually replace the C-141, the current backbone of peacetime military airlift operations. The C-17 will also supply services now provided by a limited number of C-130 tactical transports. Thus C-17 pilots must be trained to fly not only the intertheater airlift missions now accomplished by the C-141, but also the intratheater airlift missions now accomplished by the C-130 (see Fig. 1.1). During wartime, pilots will exploit the C-17's dual capabilities to deliver wartime loads directly to small, austere airfields by flying demanding short takeoff and landing (STOL) profiles. In contrast, during routine peacetime operations, pilots will principally be delivering cargo to conventional airfields with long runways.

As a consequence, C-17 aircrews will depend heavily on their flight simulators to develop and maintain the skills, knowledge, and confidence required to successfully execute the wartime tactical airlift portion of the C-17 mission. These simulators will have to provide an adequate representation of the important types of information, or cues, that aircrews use to control their aircraft, especially those cues experienced in wartime situations.

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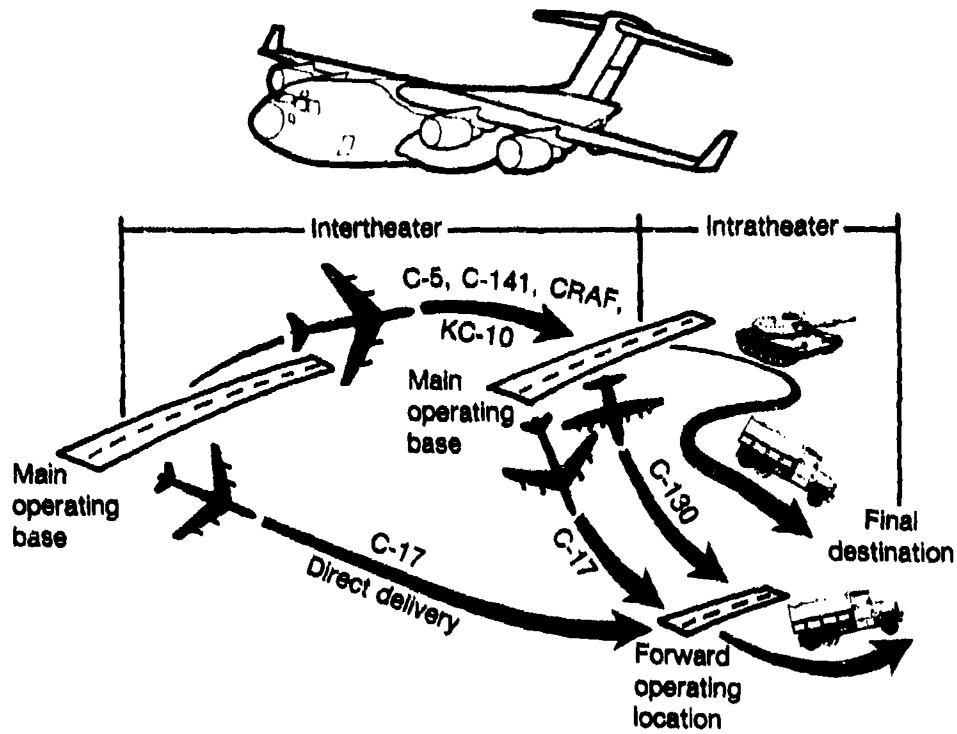
[1]For descriptions of how aircraft features influence the motion of the C-17, see App. B in N-2301-AF; for descriptions of how the stability and control augmentation system (SCAS) may influence the motion of the C-17, see App. C in N-2301-AF.

[2]By contrast, the C-141 has a crew ratio of 4.0, with two active crews and two reserve crews for each aircraft (see *USAF Cost Planning Factors*, AFR 173-13).



SOURCES: Douglas Aircraft Company, *C-17 Preliminary Design Review (PDR): Reliability and Maintainability*, May 1985, p. 505; Department of the Air Force, *U.S. Air Force Airlift Master Plan*, 1983, p. II-9.

Fig. 1.1—The C-17 and its concept of airlift operations

FRAMEWORK FOR ASSESSING SIMULATOR FIDELITY REQUIREMENTS

The framework we have employed first involves screening various candidate simulators to identify the ones that perform best for each generic type that has some prospect of fulfilling the training needs.

We then assess the potential benefits and costs of each type. The benefits include the subjective considerations of crew members and instructors, improvements in safety, avoidance of simulator sickness, and increases in simulator training capability. The costs include fiscal costs and decreases in the amount of time the simulator is available.

Increases in training capability are particularly difficult to measure, especially for an aircraft like the C-17, which currently lacks both a

simulator and a training syllabus.[3] To surmount these problems, we devised a methodology described in Sec. II.[4]

Finally, the framework involves comparing benefits and costs using a "scorecard" method.[5] This method enables the decisionmaker to see patterns and give different weights to the various tradeoffs that must be made between costs and benefits of competing simulator options. In the scorecards used in this report, each column shows the benefits and costs of a single simulator option (no-motion, g-seat, and motion platform) and each row shows the values of these benefits or costs. When expressed in numbers or words, these values convey whatever is known about the size or direction of the effect in absolute terms. Finally, shading is used to rank the benefits and costs of each simulator option: white designates the best value, black the worst, and gray the intermediate one. These rankings consider each benefit and cost separately. Thus each ranking involves a comparison between columns on a single row; it does *not* involve comparisons between rows.

SCREENING OF ALTERNATIVES

To facilitate comparisons of motion system alternatives, we selected the best performing example for each generic type of motion device that had some prospect of filling the C-17 training need.

Numerous motion cueing devices have been proposed or used.[6] For each generic type of motion device, we applied the following criteria to narrow the list of alternatives:

1. Reject alternatives incompatible with transport operations.
2. Reject alternatives that cannot treat critical mission requirements.
3. Consider only production alternatives that have been used in training.
4. Pick an alternative that provides the most complete set of cues.

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[3]The contract for the C-17's full-scale engineering development was signed on January 2, 1986.

[4]For a more complete description, see App. E in N-2301-AF.

[5]This "scorecard method" was developed at The Rand Corporation (see L. G. Chesler and B. F. Goeller, *The STAR Methodology for Short-Haul Transportation: Transportation System Impact Assessment*, The Rand Corporation, R-1359-DOT, December 1973). For a more recent discussion of this method, see E. S. Quade, *Analysis for Public Decisions*, 2d ed., North-Holland, New York, 1982, pp. 217–221.

[6]For further information on simulator motion cueing devices, see App. D in N-2301-AF.

These criteria led us to reject such devices as g-suits, helmet and arm loaders, and a host of other techniques for simulating the motion cues experienced in high-g fighter aircraft.

For our analysis, however, we did retain a *g-seat*—originally designed for fighter aircraft simulators—because it was thought to have some potential for satisfying a transport simulator's motion requirements. For this generic alternative, a seat driven with a combination of hydraulic and pneumatic actuators provides the most complete cueing (see Fig. 1.2). To impart motion cues, g-seats directly stimulate the body's haptic sensory system (which encompasses the sensations of touch, temperature, pressure, muscles, and skeletal joints) and—to a much lesser extent—the vestibular system (which encompasses the semicircular canals and otoliths of the inner ear). G-seats do so through the symmetric or asymmetric inflation and deflation of

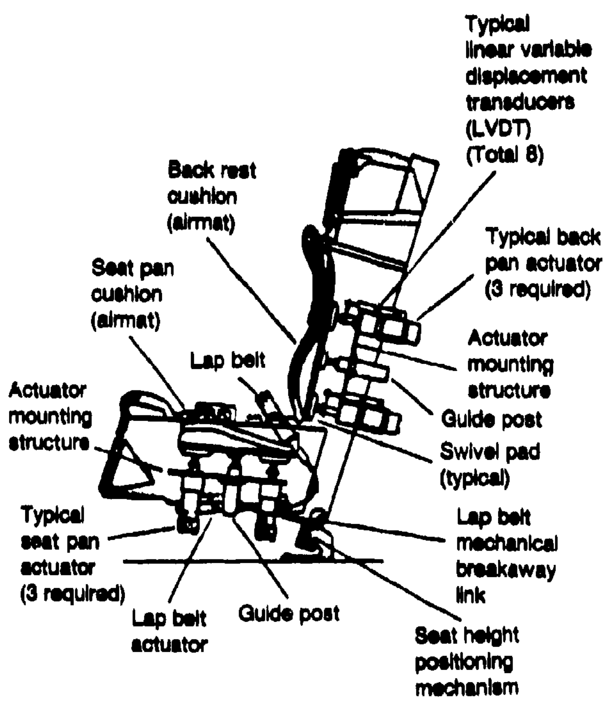


Fig. 1.2—Hydraulic/pneumatic g-seat

pneumatic bladders or bellows, the translation and rotation of seatpans and backrests by hydraulic actuators, and the constriction or relaxation of lap or shoulder harnesses by pneumatic or hydraulic actuators.

In addition, we evaluated a *six-degree-of-freedom (dof) motion platform*, the current standard for transport aircraft simulation (see Fig. 1.3).[7] The prime virtue of this platform is its ability to generate motion cues that primarily stimulate the human vestibular system and, to a lesser extent, the haptic system. By rolling or pitching in a subliminal manner, the platform can also generate sensations of sustained cues, particularly for transport aircraft that typically experience far lower sustained accelerations than do fighter aircraft.

The third alternative, a simulator with *no physical motion system*, relies on changes in its visual display, flight instruments, and control forces to induce the sensation of motion.

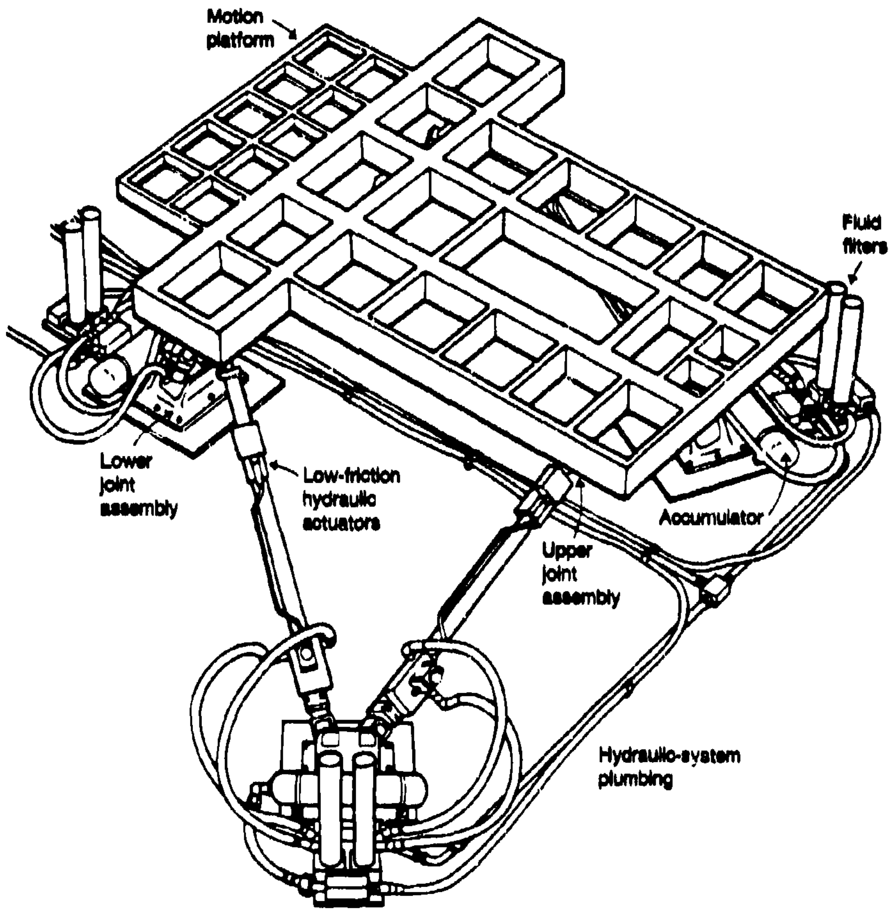
In brief, then, we evaluated simulators with

- No-motion system
- Combined hydraulic/pneumatic g-seats
- A six-dof motion platform.

Narrowing the list to three alternatives was partly to keep the analysis manageable, but it also reflects some technical and marketplace realities. As we shall see, even the most capable g-seat alternative has difficulty supplying a full range of motion cues, and hence it would be pointless to evaluate lower-fidelity g-seats. Motion platforms with fewer than six dof might satisfy many military transport simulator motion requirements, but the industry standard today is the six-dof synergistic platform, and the industry is geared to produce such platforms in quantity for its civil and military customers.

For the no-motion, g-seat, and motion platform alternatives, we assumed that all other capabilities of the simulator—such as aural stimuli, instruments, flight control, and visual simulation—would be the same. The visual system assumed here is of mid-quality with computer-generated imagery, full-daylight and full-color facsimile capability, and five screens and four channels to provide a wide field of view.

[7]There are more costly and more complex six-dof research simulators capable of larger angular excursions and translational displacements. However, the onset cues generated by standard six-dof simulators have proved adequate for simulating most transport aircraft maneuvers (see App. D, N-2301-AF).



SOURCE: The Singer Company, Link Flight Simulation Division

Fig. 1.3—Six-dof synergistic motion platform

FINDINGS

If the Air Force uses flight simulators with an adequate training syllabus, and if adequate aircraft performance data are collected during flight testing to support simulator software development, then a six-dof motion platform for the C-17 would yield significant benefits in terms of flight safety and enhanced war-fighting capabilities. Because they

offer greater cueing capability than other alternatives, such motion platforms would probably also provide protection against unknown risks caused by omitting motion cues during training, especially for young and inexperienced aircrews. The relatively modest costs of motion platforms appear justified by these likely benefits. A combined hydraulic/pneumatic g-seat does not appear to be a cost-effective alternative, nor does a no-motion platform.

OUTLINE OF THE STUDY

Section II summarizes the assessment of benefits, Sec. III summarizes the assessment of costs, and Sec. IV presents conclusions. Further supporting details and a complete bibliography appear in companion Note N-2301-AF.

II. ASSESSMENT OF BENEFITS

A simulator's design features can affect many types of benefits that its users will experience. We considered four types:

- Subjective considerations involving crew confidence, instructor confidence, and training efficiency
- Improvements in safety
- Avoidance of simulator sickness
- Increases in simulator training capability

We did not assess several others,[1] because we believed either that they were equal across all three simulator alternatives or that they increased with the fidelity of the motion system. Thus, our conclusion that the motion platform is the preferred alternative appears robust, because including these neglected benefits would have made the motion platform appear all the more preferable.

SUBJECTIVE CONSIDERATIONS

Extensive interviews[2] with pilots of various large multiengine aircraft revealed three types of concerns involving the presence or absence of motion in simulators: crew confidence, instructor confidence, and training efficiency.

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[1]Among the potential benefits we did not assess were (1) improved engineering development and testing, (2) improved investigation of accidents, (3) improved mission planning, (4) improved development of tactics, (5) reduced noise and emissions from aircraft, (6) reduced energy consumption, (7) increased readiness in times of energy shortages, (8) reduced stress on aircraft, (9) improved proficiency of pilots with desk jobs, and (10) improved training for maintenance personnel.

[2]We interviewed over 50 Air Force pilots and copilots at the 2nd Strategic Bomb Wing at Barksdale Air Force Base, Headquarters Military Airlift Command, Headquarters Strategic Air Command, the 314th Tactical Airlift Wing at Little Rock Air Force Base, and the Aeronautical Systems Division. We also interviewed over 20 pilots and copilots at the VP-31 P-3 Training Replacement Squadron, the United Airlines Aircrew Training Corporation, the American Airlines Training Corporation, the American Airlines KC-10 Training Center at Barksdale Air Force Base, the Seville Training Systems Corporation, the Naval Training Equipment Center, Headquarters of the Federal Aviation Administration, the Douglas Aircraft Company, and the Lockheed-Georgia Company.

Crew Confidence

Many Air Force aircrews we interviewed were young and relatively inexperienced compared with their airline counterparts. Once the C-17 replaces the C-141, we can reasonably expect that many aircrew members will have had no prior experience flying large multiengine aircraft. This will place added demands for effectiveness on training simulators.

The KC-10 crews we interviewed at Barksdale Air Force Base expressed strong support for the training program being provided by American Airlines under contract to the Air Force. They especially praised the KC-10 flight simulator. They indicated, for example, that they had great confidence in the simulator because it realistically replicated the visual and motion cues they experienced when actually flying the KC-10. Thus when crews practice emergency procedures that because of their dangerous nature can only be practiced in the simulator, they can be confident that the simulator provides a faithful representation of what they will encounter in the airplane. And since their first indication of many emergency situations comes via motion cues, they were especially adamant about the need to have these cues in the simulator.

Instructor Confidence

The Air Force currently uses simulators to perform a number of aircrew checks, thus freeing airplanes for mission-oriented training. In the KC-10 program, for example, all instrument flight checks and emergency procedure checks are performed in the simulator.

The KC-10 instructor pilots we interviewed indicated they would have little confidence in performing instrument checks in a simulator that did not provide motion cues to aircrews and instructor pilots. Instructor pilots rely on the motion and feel of the simulator in evaluating the performance of the aircrew member during instrument checks. Instructor pilots indicated that instead of lobbying to get more checks transferred from the aircraft to the simulator, as they are now doing, they would lobby to put the checks back in the airplane if the simulators lacked a motion platform.

Many instructors also say that students tend to overcontrol in simulators that lack motion.[3] This is especially true for such situations as

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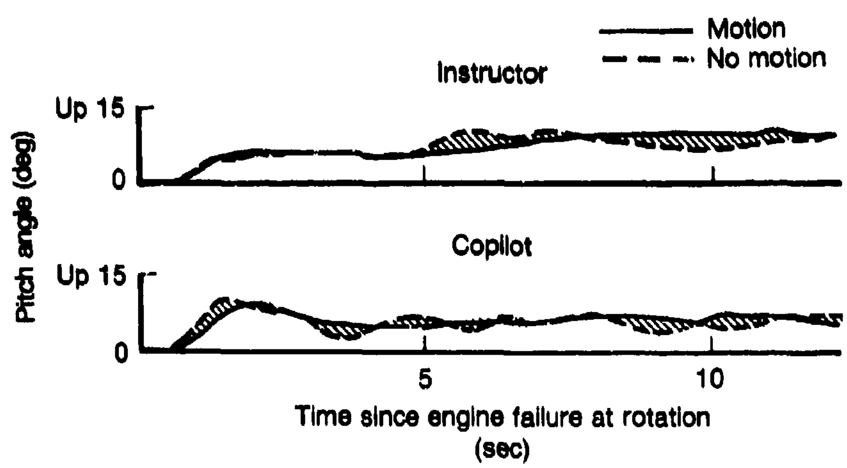
[3]Experiments lend support to this view; see, for example, W. G. Matheny et al., *An Experimental Investigation of the Role of Motion in Ground-Based Trainers: Pilot Training Devices*, Final Report, 12/70-6/73, NAVTRAEQUIPC-71-C-0075-1, 1984; B. Parris and A. Cook, *Effects of Visual and Motion Simulation Cueing Systems on Pilot Performance During Takeoff with Engine Failures*, NASA Technical Paper 1365, December

engine failure, in which the first indication of the failure is a change in aircraft motion (see Fig. 2.1). If the change in motion does not occur in the simulator, then the pilot must respond to visual or instrument cues that are normally sensed some time *after* the human vestibular and haptic sensory systems would sense a change in motion. Without the motion cue, the student is thus delayed in his responses. In attempting to correct for this delay, the less experienced student tends to overcorrect. And when he realizes he has overcorrected, he then tends to overcorrect in the opposite direction.

Instructor pilots are especially concerned that students not develop overcontrol habits during simulator sessions. Many believe that this will happen in the absence of motion cues. Overcontrol is most dangerous in emergencies, such as engine failure, and when the aircraft is near the ground during takeoff and landing.



SOURCE: Data collected especially for this study by the 314th Tactical Airlift Wing at Little Rock Air Force Base.

Fig. 2.1—Illustration of overcontrol without motion

1978; and J. M. Rolfe et al., "Pilot Response in Flight and Simulated Flight," *Ergonomics*, Vol. 13, No. 6, November 1970, pp. 761–768.

Training Efficiency

The people we interviewed generally agreed that simulators enable more efficient use of both personnel and aircraft by providing more intense, time-efficient training. For instance, a pilot can repeatedly practice landing approaches in a simulator with less expense of his and an instructor's time than he could in an airplane. (Without a simulator, a pilot must repeatedly takeoff and reenter the landing pattern to reach the landing approach point.) As will be illustrated later, this efficiency can potentially be exploited across a broader range of training tasks in simulators that have motion platforms.

Simulators can also reduce exposure of the C-17 airframe to structural fatigue damage during peacetime. Much tactical-mission training in the C-17 will occur at low altitudes, where airframes can accumulate fatigue damage at a rate six to eight times that experienced at higher altitudes. Simulators with motion may allow the Air Force to transfer some of this training to the simulator, training crews to operate in the turbulent environment of low-altitude flight without shortening the operational life of the airplane.

IMPROVEMENTS IN SAFETY

To examine whether incorporating motion in simulators might benefit flight safety, we investigated accident experiences of commercial air carriers and the U.S. Air Force.[4]

Commercial Air Carrier Training Accidents

Motivated by concerns about flight safety and economy, U.S. air carriers during the late 1960s asked the Federal Aviation Administration (FAA) for permission to perform certain training and checking events in flight simulators rather than in aircraft. Flight safety was a major concern because aircrews typically operated aircraft in potentially dangerous areas of the flight envelope to accomplish in-flight training of simulated emergencies. American Airlines reported their accident rate during in-flight training was five to seven times greater than that during normal operations. Economic concerns arose as a result of the imminent introduction of wide-body aircraft, which promised to increase training costs dramatically in the absence of some new training approach.[5]

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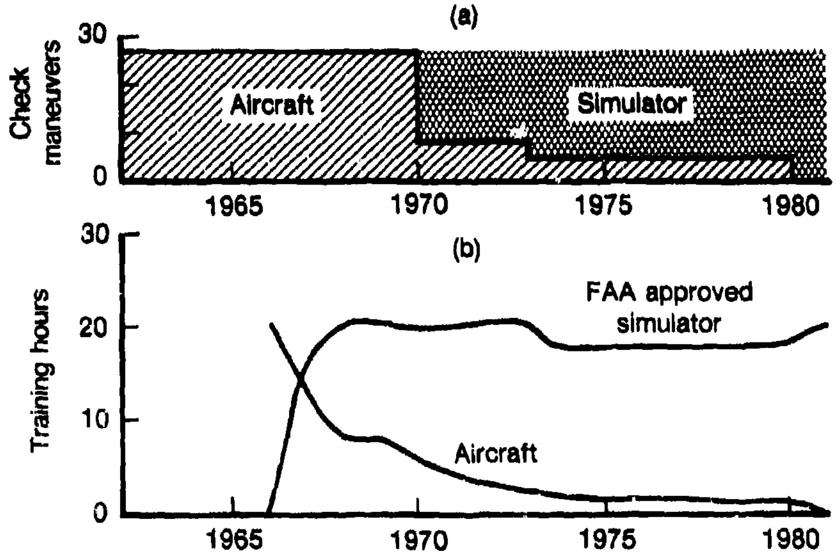
[4]For further information, see App. G in N-2301-AF.

[5]See R. D. McLure and H. A. Kottman, *Parallelism in Commercial and Military Use of Simulation*, Conference Proceedings, American Institute of Aeronautics and Astronautics, Paper No. 75-971, August 4-7, 1975.

Progressive improvements in visual, aural, and motion systems, and in aerodynamic data bases for flight simulators, resulted in a series of FAA rule changes that increased the training and checking of pilots allowable in simulators (see Fig. 2.2a). By the end of 1980, FAA rules permitted virtually all training and checking to be accomplished in simulators that met FAA standards for visual and aural systems, aerodynamic programming, and six-dof motion platforms. Figure 2.2b shows how American Airlines, by introducing increasingly capable simulators, was able to reduce the B-727 flying-hours needed to promote a copilot to captain from 20 hours to zero hours. Those flying-hours were dedicated exclusively to training; with no passengers on board, the airplane generated no revenue. Today, all such training occurs in simulators.

Safety records for the airline industry have improved during this era of increased reliance on simulators (see Fig. 2.3a).[6] Many people



SOURCES: R. D. McLure and H. A. Kottman, *Parallelism in Commercial and Military Use of Simulation*, Conference Proceedings, American Institute of Aeronautics and Astronautics, Paper No. 75-971, August 4–7, 1975; personal communication with J. L. Mansfield, Manager, Flight Training Operations, American Airlines.

Fig. 2.2—American Airlines shift of training to simulators (promotion of copilot to captain)

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[6]Figure 2.3a expresses this improvement in absolute terms (i.e., total number of accidents). Between 1962 and 1980, the rate of accidents per mile flown by U.S. certifi-

involved with flight simulation believe that the improvements are at least partly due to the higher quality of training provided by simulators. The improvements are certainly also due to improved engines and airplane design, and perhaps also to improved air traffic control, airports, and airways.

Although we cannot precisely measure the safety improvement attributable solely to increased reliance on simulators, we do know that the progressive shift of training from the airplane to the simulator has reduced exposure to training accidents and thus has helped reduce the absolute number of training accidents (see Fig. 2.3b). Obviously, when air carriers perform *all* their training and checking in flight simulators, as is done today, aircraft training accidents go to zero. The computerized data base we used from the National Transportation Safety Board, complete through 1982, shows that no air carrier training accidents have occurred since 1979.

All FAA-approved simulators for commercial airline training use some form of three- to six-degree-of-freedom motion platform system (most commonly six-dof systems), depending on the level of training for which the simulator is approved. Just as we cannot sort out the simulator's contribution to improvements in overall accident statistics, so we also cannot sort out the marginal contribution to safety made by motion platforms. But the kinds of training accidents that occurred between 1962 and 1979 provide a clue about the importance of motion cues in helping crews to respond properly to malfunctions that can lead to accidents.

The cross-hatching in Fig. 2.3b shows that 10 of the 40 training accidents occurred during simulated malfunctions of propulsion systems. Another 6 accidents involved actual malfunctions of propulsion systems. Most of these 16 accidents occurred during takeoff or landing, when reaction time is especially important. Most pilots and human factors experts we interviewed stated that motion cues are particularly important for quick awareness of such malfunctions, for promptly responding with control inputs, and for exerting continuing control over the aircraft. This points to the value of incorporating motion in a simulator. Training in a simulator capable of accurately representing the motion cues experienced during such in-flight malfunctions, as a motion platform can, may help crews develop the proper control responses to avoid accidents. Inherent design constraints of the no-motion and g-seat alternatives prevent them from adequately representing many of the rapid roll, lateral, and yaw motions experienced during transport aircraft emergency situations.

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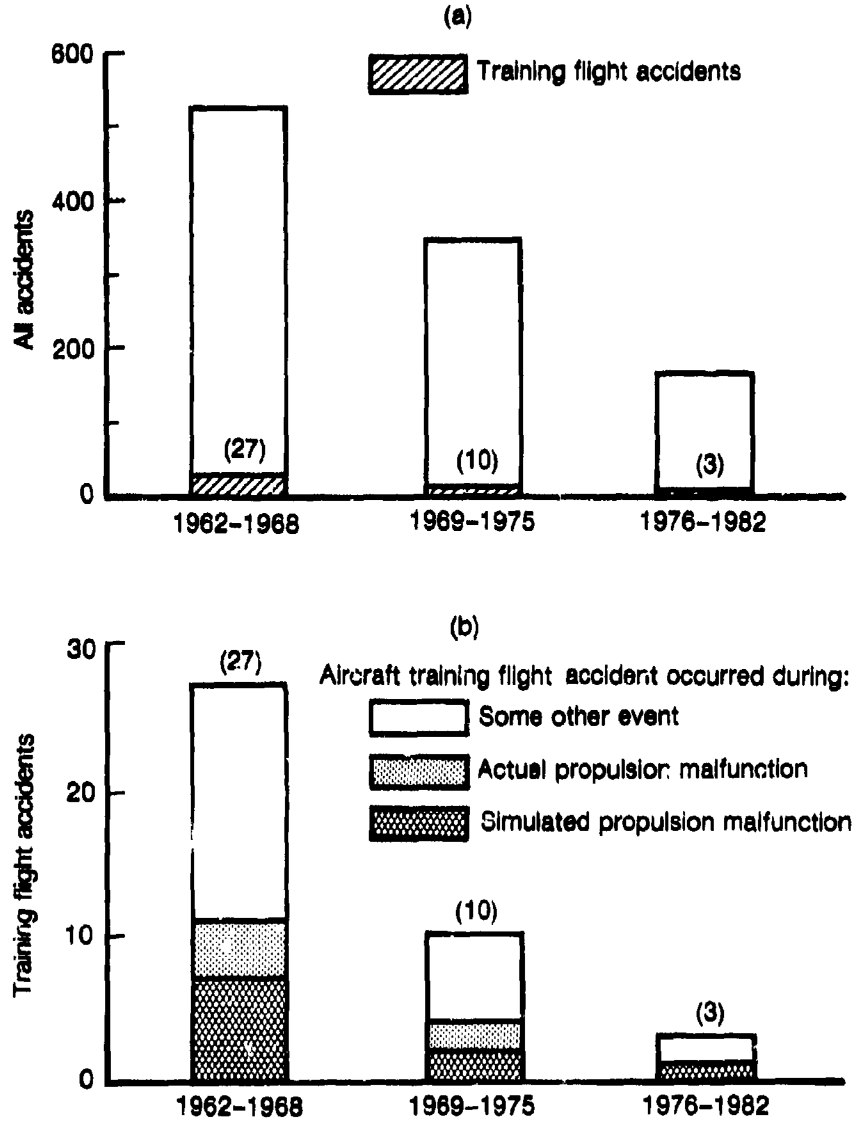
cated route and supplemental air carriers also declined, in this case by about 80 percent (reported by National Transportation Safety Board staff).

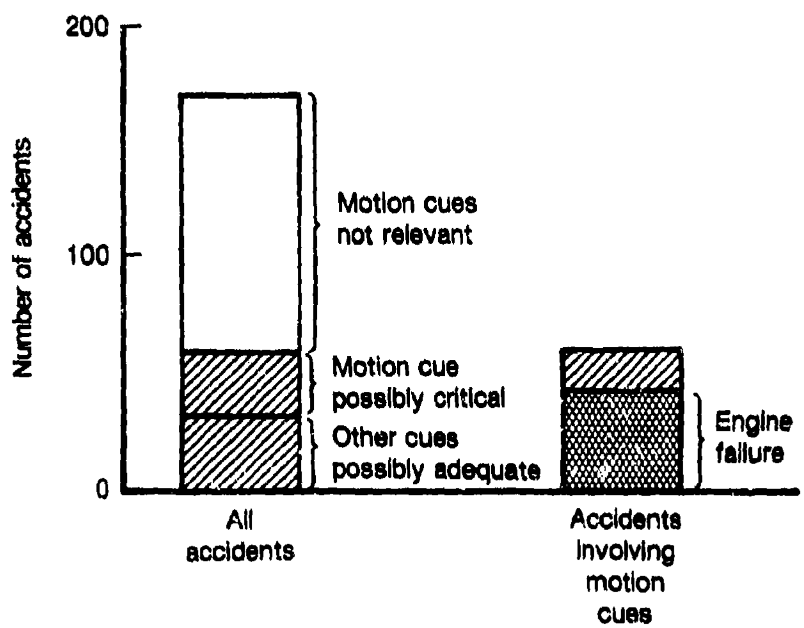


SOURCES: Review of National Transportation Safety Board Briefs of Aviation Accidents; *Annual Review of Aircraft Accident Data, U.S. Air Carrier Operations*, National Transportation Safety Board, various years; *FAA Statistical Handbook of Aviation*, U.S. Department of Transportation, Federal Aviation Administration, various years.

Fig. 2.3—Decline in U.S. certificated route and supplemental air carrier accidents

Air Force Accidents

Our conservative engineering review of ten years of Air Force accident experience with noncenterline-thrust aircraft like the C-17 indicates that roughly 15 percent of all accidents involved situations in which motion cues play a major role in alerting the pilot to potential dangers—and most of these involved engine failures (see Fig. 2.4). Again, then: Simulators with motion may be valuable for better preparing flight crews for dealing with potential in-flight dangers that involve motion cues.



SOURCE: Detailed review of Air Force accident records supplied by the Air Force Inspection and Safety Center, Norton Air Force Base.

Fig. 2.4—Air Force accidents with noncenterline-thrust aircraft (1975–1985)

AVOIDANCE OF SIMULATOR SICKNESS

Either during or after sessions in a flight simulator, pilots occasionally experience nausea, stomach upset, disorientation, and other abnormal physiological sensations. Such symptoms have not been reported often enough to arouse great concern, but they can reduce the value of training sessions by distracting pilots, and they can discourage pilots from using simulators again. The results could be more poorly trained aircrews, decreases in operational readiness, and poor returns on the investment in simulators. After-effects such as disequilibrium can be dangerous when a pilot drives an automobile or flies an aircraft.

We do not know for certain what causes simulator sickness.[7] One hypothesis is that sensory conflict induces it—for example, if a simulator provides good visual cues but fails to provide motion cues, thus presenting one situation to the eyes and another to the body. Our interviews suggest that experienced pilots may be more prone than others to this kind of simulator sickness. Their eyes and bodies have become accustomed to certain cues, and they become confused when they fail to encounter these cues.

The Navy's current simulator program lends some credibility to these concerns. It requires all simulator facilities to report the incidence of simulator sickness symptoms, and, in certain situations, policies set by local base commanders restrict crew members from flying within 12 hours after training in a simulator.

If sensory conflict does indeed lead to simulator sickness, then aircrews using the no-motion alternative run the greatest risk of simulator sickness. The g-seat reduces this risk somewhat, and the six-dof motion platform reduces it most.

INCREASES IN SIMULATOR TRAINING CAPABILITY

The Problem of Assessing Simulator Effectiveness

Ideally, one would want quantitatively to assess the training effectiveness of simulators with no motion, with g-seats, and with motion platforms by comparing an aircrew member's performance in different kinds of simulators with his overall performance in the airplane while executing a full range of tasks under a full range of environmental and combat conditions. Some tasks are too dangerous to practice in an aircraft, however, and some environmental and combat conditions are too

[7]For further information, see App. H in N-2301-AF.

difficult to control. Thus we often cannot observe an aircrew member perform tasks in an aircraft under the same conditions that he practiced in a simulator. As a consequence, we face the very difficult question of whether performance in the simulator transfers to proficiency in the airplane.

Researchers have attacked that question at two levels.

At one level, they have explored physiological and intellectual processes, including cue-sensing systems, information processing, and psychomotor responses. Although much has been learned, these processes and interactions still cannot be thoroughly modeled, and the question remains unanswered.

At the next level, various experiments have focused on safe maneuvers that can be trained in the simulator and executed in the airplane. Obviously, such experiments must exclude dangerous maneuvers and environmental and combat conditions that are beyond the control of the experimenter. Even with this narrowed focus, these experiments have stirred much debate.[8]

We found mixed results when we surveyed pilots and instructors in 24 experiments that tried to determine whether motion cues in flight simulators improve pilot performance in the airplane: 9 claimed they help,[9] 14 claimed they have no effect, and one claimed they are detrimental (see Fig. 2.5). These mixed results may derive from a number of problems. For one thing, most experiments before 1979 used older platform motion systems that provided poor motion cues.[10] In addition, many experiments—both before and after 1979—used centerline-thrust aircraft. Our interviews and review of the literature suggest that different types of motion cues may be important to those aircraft and are inherently difficult for a platform to represent. Taken in sum, these experiments fail to answer the question of whether motion cues in simulators improve pilot performance.

Our Approach to Assessing Simulator Training Capability

Notwithstanding this lack of knowledge, we must make choices about features for our simulators. One way to assess the training capability of a simulator is to examine the tasks and conditions identified in the training syllabus, and determine whether a particular simulator can provide the cues needed to train those tasks with their associated environmental and combat conditions.

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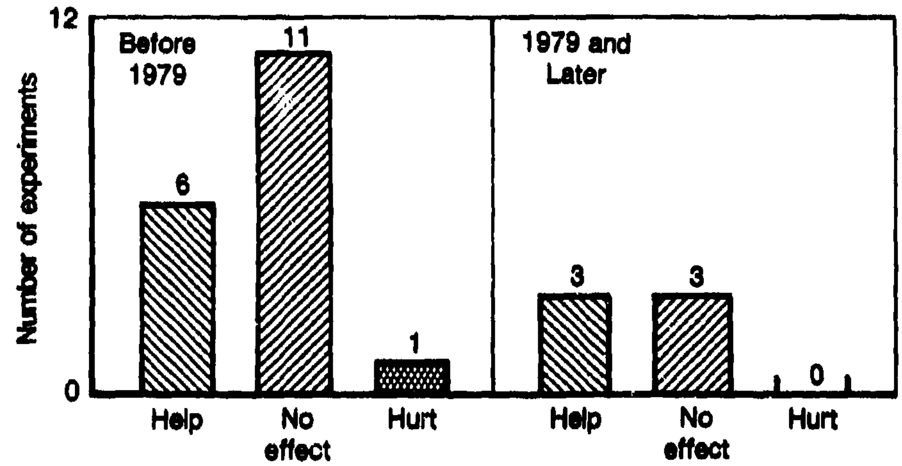
[8]For descriptions of these experiments and their specific and innate limitations, see App. A in N-2301-AF.

[9]These typically claimed that the benefit of motion is not large.

[10]For more details about some of the design shortcomings of early motion systems, see App. D in N-2301-AF.



SOURCES: See bibliography.

Fig. 2.5—Effect of motion cues on pilot performance observed in experiments

For the C-17, however, we lack both a simulator and a syllabus. In the absence of a syllabus, we might rely on those of the aircraft the C-17 will replace (the C-141 for intertheater and the C-130 for intratheater missions). However, the C-130 syllabus needs considerable revision to take better advantage of the training capabilities of its simulator's visual and motion features. To this end, the Air Force is currently funding a study called Model Aircrew Training System[11] to define the requirements that could be specified for the development of a new syllabus for the C-130. Any current decision, therefore, about C-17 simulator features must be made in the absence not only of the C-17 syllabus but also of an analogous one.

For our analysis, therefore, we drew up a list of tasks and conditions that are potential candidates for inclusion in the eventual C-17 syllabus. We then assessed the capability of each of the three simulator alternatives to provide an adequate set of cues for training each task in

[11]A joint effort by the Air Force Human Resources Laboratory and the Military Airlift Command.

a variety of conditions (see Fig. 2.6 for a summary of our approach and App. E in N-2301-AF for a detailed description).[12]

In arriving at our list of flight tasks, we developed a minimum set that represented the full spectrum of the hundreds of tasks that aircrews will perform. The resulting task list was divided into four groups:

- 25 *basic tasks*, including typical flight-check events such as takeoff, departure, and cruise
- 19 *additional maneuvers*, including gear extension/retraction, stall recovery, direct lift control spoiler extension/retraction, and short-field landing
- 23 *malfunctions*, including failures of the stability and control augmentation system, one engine failure in flight, asymmetric/split flaps, and air drop extraction failure
- 9 *combat tasks*, including low-level cruise, low-altitude parachute extraction, air drop, and assault landings

Many of the above tasks can be performed under various types of environmental and combat conditions (see Fig. 2.6). For example, a basic task such as an approach for landing can be made under varying wind-related and load conditions. It seems reasonable to believe that the C-17 syllabus would specify training approaches not only in the absence of such conditions but also in their presence. Although the C-17 syllabus may not, for example, require training an approach for landing under all six wind-related conditions in Fig. 2.6, it seems reasonable to believe that it would require training in at least several of them.

The heart of the training capability assessment method we use here lies in the counting of tasks and condition-related variations on tasks that would be trainable in a particular simulator. Whether a task is *trainable* in a particular simulator under specified conditions depends

[12]As part of our methodology, a pilot on the Rand research team drew on four sources to construct a comprehensive list of potential tasks. The list was reviewed by a second pilot who is currently a P-3 pilot in the Naval Reserve. The four sources were *A Systematic Determination of Skill and Simulator Requirements for Airline Transport Pilot Certification*, DOT/FAA/VS-84-1, November 1984; *Prime Item Development Specification for C-17 Air Vehicle*, Specification MDC S002, Douglas Aircraft Co., McDonnell Douglas Corporation, Vols. 1 and 2, April 1, 1983; C-130 manuals; and C-141 flight manuals. The FAA report dealt with tasks for first pilot upgrade in a Boeing 727. They included check tasks, training tasks, and maneuvers. From this task list we extracted those tasks common to all large multiengine aircraft. This task list obviously lacked combat tasks and tasks unique to the C-17. We drew these from the C-17 system specification and other sources. The C-130 manuals included the -51 and -55 series for training, combat maneuvers, and tasks and the standard evaluation check list. The C-141 manuals included the aircrew continuation training and emergency procedures list.

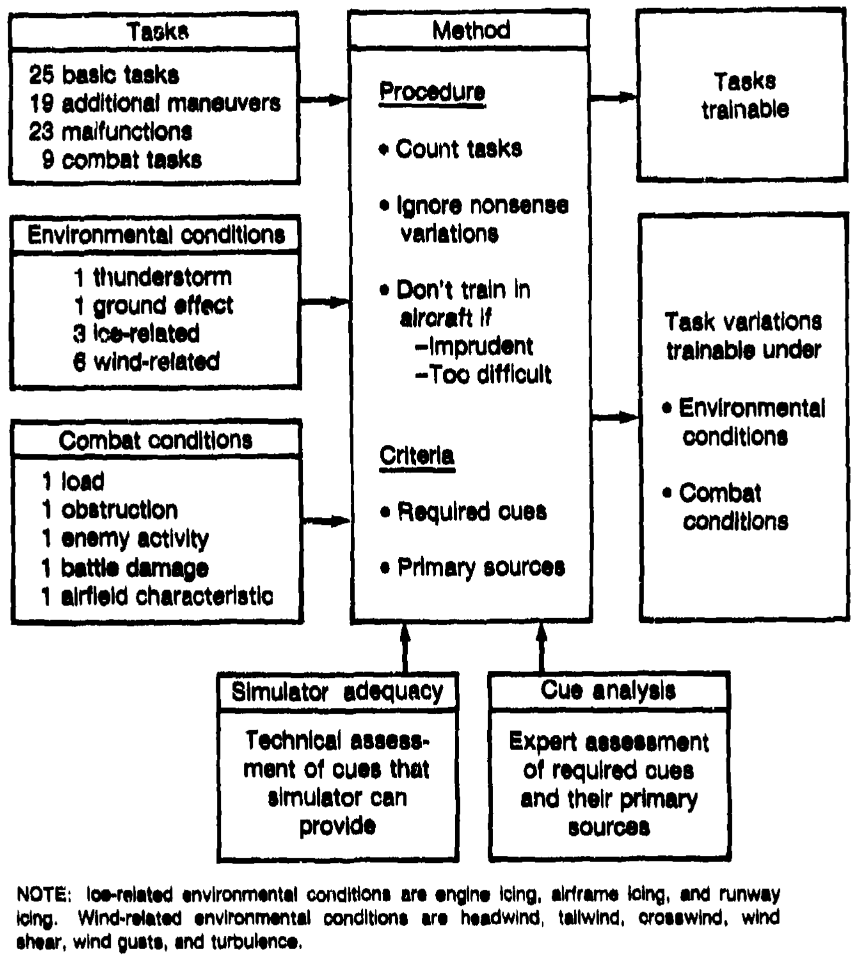
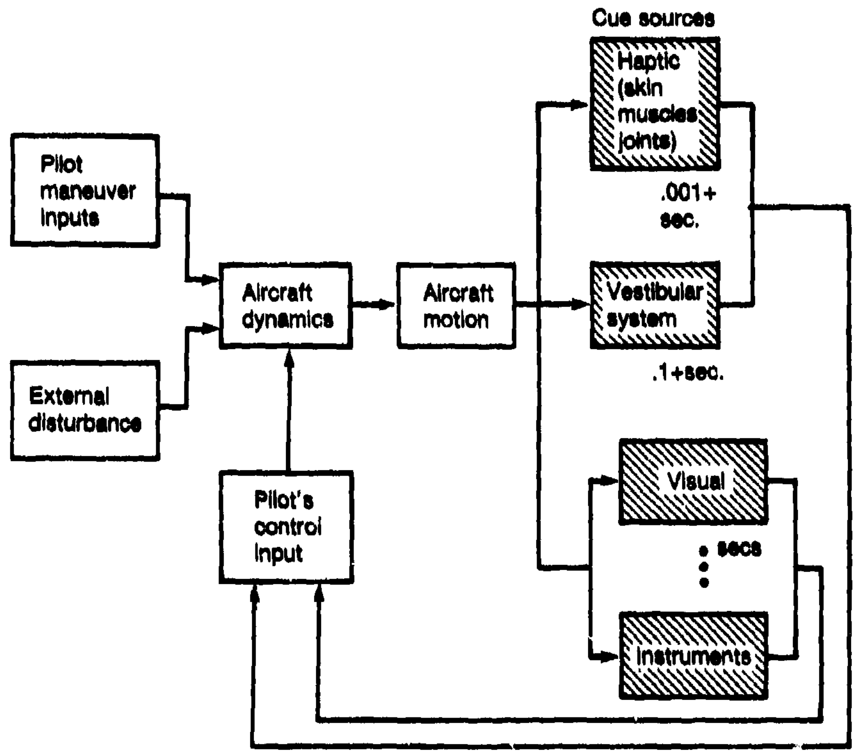


Fig. 2.6—Approach to assessing simulator training capability

on the ability of that simulator to provide the cues that the pilot would use to control the aircraft while executing the task.

Figure 2.7 illustrates how and when the various sources and types of cueing information play a role in controlling aircraft motion. Haptic cues reach the pilot before vestibular cues, and both reach the pilot before visual and instrument cues.



SOURCES: Adaptation of figure provided by the Singer Company, Link Flight Simulation Division; E. A. Martin, *Motion and Force Simulation Systems*, Chap. 10 of short course on simulation sponsored by the Air Force Institute of Technology; "Physiological Factors," *Fidelity of Simulation for Pilot Training*, pp. 13–18, AGARD, Neuilly-sur-Seine, France, AGARD-AR-159, December 1980; R. L. Stapleford et al., *Experiments and a Model for Pilot Dynamics with Visual and Motion Inputs*, NASA-CR-1325, TR-168-2, Systems Technology, Hawthorne, Calif., May 1969.

Fig. 2.7—Control of aircraft motion

Flight operations analysis of cues involves determining what kinds of cues are required in a simulator to perform a task as it would be performed in the aircraft.[13] This poses two major problems.

First, one could claim that simulators do not need to display motion cues experienced while flying an aircraft. It has been argued, for

[13]The state-of-the-art of this type of analysis is still relatively new and evolving. Prior to this study, the most recent and most thorough application of it was in D. C. Gilliom et al., *A Systematic Determination of Skill and Simulator Requirements for Airline Transport Pilot Certification*, Final Report, U.S. Department of Transportation, Federal Aviation Administration, DOT/FAA/VS-84/1, Washington, D.C., November 1984.

example, that pilots will learn to recognize motion cues during routine flying situations and then transfer this recognition when training in a simulator that lacks motion cues. As we have seen earlier, however, the lack of motion cues can cause pilots to overcontrol, which is most dangerous during emergencies, such as engine failure, and when the aircraft is near the ground during takeoff and landing. Thus for the purposes of this analysis, we do not omit motion cues when determining the kinds of cues required in a simulator to perform various tasks in the aircraft.

Second, in preparing the C-17 syllabus the Air Force may choose less stringent criteria for considering a task trainable in a simulator. Lacking both a C-17 syllabus and an acceptable C-130 syllabus, we thought it unreasonable to presume less stringent criteria for this analysis, especially since we are dealing with safety issues and with valuable resources including the airplane, its crew, its passengers, and its urgently needed wartime load.[14]

In our flight operations analysis, we designate a cue as a *primary* cue for a particular task in controlling the airplane if it is either the first indicator of an external disturbance or the most important source of information used in controlling the airplane.[15] We designate a task (or a task in a specified environmental or combat condition) as "trainable" in a particular simulator if, and only if, the simulator provides *all* primary cues the pilot uses to control the aircraft. If it does not, either it lacks some cues that the pilot will find necessary or it provides those cues from substitute sources. Thus it trains the pilot to perform the task differently in the simulator than he would in the aircraft.

We used the cues and priorities developed by Gilliom et al. to determine the primary cues required for each task. For most of those tasks that the C-17 has in common with other transport aircraft, we used the cues Gilliom developed for the Boeing 727. For tasks specific to the C-17, two experienced pilots and a human factors specialist on the Rand staff assigned cues, using the rationale for cues embodied in Gilliom and adapting cues of similar maneuvers.

Deciding whether a simulator can provide the primary cues required for training a task involves a technical assessment of simulator cueing adequacy. This adequacy is determined by identifying which of the cues needed to perform tasks in the aircraft can be provided by the

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[14]In dealing with realities, the Air Force may have to accept certain compromises involving the frequency and degree of realism that it can provide when training specific tasks and conditions. Such compromises are most appropriately left for those who will develop the C-17 training syllabus.

[15]In so doing, we follow the approach used by Gilliom et al.

simulator. In the no-motion alternative, the simulator cannot provide force-induced motion cues—although it and the other two alternatives do provide the same visual- and instrument-induced sensations of motion as well as flight control forces. Although g-seats have never been used in an operational transport aircraft simulator, there is some evidence—both from objective experiments and from subjective impressions of users—that g-seats can provide some measure of motion cueing in vertical and longitudinal axes. However, inherent design characteristics of g-seats severely limit their ability to provide adequate representations of roll, lateral, and yaw motions. These latter motion cues are particularly important to ensuring that pilots can recognize and recover from many transport emergencies, such as engine failures. Thus in terms of the quality and diversity of motion cues it can represent, the g-seat alternative is decidedly less capable than the motion platform alternative, which can provide the full spectrum of motion cues involved in the operation of transport-type aircraft (see App. D in N-2301-AF).

RESULTS OF ASSESSING SIMULATOR TRAINING CAPABILITY

We applied the simulator training capability assessment methodology to answer three key questions. (1) How many tasks and variations of tasks can each simulator alternative train? (2) How many can be trained only in the airplane? (3) How many cannot be trained at all? Table 2.1, structured to address the three questions, shows the results of our assessment for (a) 76 basic tasks, additional maneuvers, malfunctions, and combat tasks, as well as for variations of the 9 combat tasks for (b) 5 types of combat conditions and (c) 11 types of environmental conditions.[16] These result in a total of 163 tasks and variations of tasks after nonsensible variations of tasks and conditions are excluded—such as coping with ice on the runway while in flight.

The differences in the totals in Table 2.1 for the various simulator alternatives arise because of differences in their ability to supply the necessary motion cues required to train particular tasks and because some tasks are either too dangerous or difficult to be trained in the aircraft.[17] Although one can answer the three key questions of interest

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[16]For detailed description of our assessments of simulator training capabilities, see App. F in N-2301-AF.

[17]For example, an engine failure at rotation for takeoff is deemed imprudent to train in the KC-10 aircraft, and consequently that training is conducted only in its simulator. A task too difficult to train in the aircraft would, for example, involve practicing repeated landings in particular crosswind conditions on demand.

Table 2.1

TRAINING CAPABILITY OFFERED BY THE THREE SIMULATOR ALTERNATIVES

Capability Category	Number of Sensible Tasks and Variations	Percentage of Sensible Tasks and Variations Trainable		
		No Motion	G-Seat	Motion Platform
Tasks and Variations Trainable in the Simulator				
Basic tasks, additional maneuvers, malfunctions, combat tasks	76	26	46	100
Combat tasks with combat condition variations	34	9	47	100
Combat tasks with environmental condition variations	53	11	11	100
Tasks and Variations Requiring Training in the Aircraft				
Basic tasks, additional maneuvers, malfunctions, combat tasks	76	51	39	0
Combat tasks with combat condition variations	34	41	24	0
Combat tasks with environmental condition variations	53	4	6	0
Tasks and Variations Not Trainable at All				
Basic tasks, additional maneuvers, malfunctions, combat tasks	76	22	14	0
Combat tasks with combat condition variations	34	50	29	0
Combat tasks with environmental condition variations	53	85	83	0

using the disaggregated results depicted in Table 2.1, the differences in the three simulator alternatives are more apparent when we aggregate results for the 163 tasks and variations of tasks, as shown in Table 2.2. The training capability of the no-motion and g-seat alternatives differs in three important ways from the motion platform alternative:

- The motion platform simulator can train many more tasks. In fact, it can train all (100 percent) of the many (163) tasks and variations of tasks, whereas the g-seat alternative can train only

Table 2.2

SUMMARY OF TRAINING CAPABILITY OF THE THREE ALTERNATIVES

Capability Category	Percentage of Sensible Tasks and Variations Trainable		
	No Motion	G-Seat	Motion Platform
Tasks and variations trainable in the simulator	18	35	100
Tasks and variations requiring training in the aircraft	34	25	0
Tasks and variations not trainable at all	48	40	0
Total[a]	100	100	100

[a]163 sensible tasks and variations.

35 percent and the no-motion simulator 18 percent of the tasks. Thus the motion platform simulator is a much more versatile training device.

- The aircraft is the only option for training many tasks (one quarter to one third) if g-seat or no-motion simulators are procured, because these simulators lack the necessary motion-cueing capabilities. Hence, their procurement could place a greater training burden on the C-17, whose availability for training will be limited because of heavy peacetime demands for military airlift services.
- Many tasks (40 percent or more) cannot be trained at all according to our training standard if the no-motion or g-seat simulators are procured. The simulators cannot provide the necessary motion cues; the aircraft cannot train the tasks because they are either too dangerous or difficult to be trained in flight. The Air Force, then, would incur an opportunity cost for not being able to train these tasks.[18]

[18]The next section develops a lower bound for this opportunity cost.

SUMMARY OF BENEFITS

Table 2.3 summarizes all the assessed benefits for the three alternatives for all considerations. The motion platform alternative offers the most prospective benefits and the no-motion alternative offers the least. The g-seat alternative offers intermediate benefits.

Table 2.3

SUMMARY OF ALL BENEFITS

Benefit Measure	Alternative Case: No Motion	Alternative Case: G-Seat	Alternative Case: Motion Platform
Subjective considerations			
Crew confidence			
Instructor confidence			
Training efficiency			
Contribution to safety			
Avoidance of simulator sickness			
Simulator training capability			
Tasks and variations trainable in the simulator	18%	35%	100%
Tasks and variations requiring training in the aircraft	[illegible]	25%	0%
Tasks and variations not trainable at all	[illegible]	40%	0%

Rankings: Best · Intermediate · Worst

III. ASSESSMENT OF COSTS

Features selected for a simulator can affect its fiscal costs[1] and availability.

FISCAL COSTS

Inclusion of either g-seats or motion platforms affects the costs of acquiring simulators, the costs of the facilities needed to house them, and the costs of operating and supporting them over a 25-year life cycle. Costs also depend on the number of simulators procured and their utilization. To investigate the effects of such uncertainties, we first performed a *basic analysis*, whereby the three alternatives were procured and utilized according to current Air Force practice for the C-141. We then performed a *sensitivity analysis*, whereby the alternatives were procured and utilized to reflect the simulators' different training capabilities.

Basic Analysis

To assess fiscal costs, we assumed that 208 primary aircraft authorized (PAA) C-17s will ultimately replace 234 PAA C-141s,[2] and that eight C-17 simulators will replace the current eight C-141 simulators at the same bases (three at the Altus Training Base and one each at the five operational bases).

To assess operational and support costs, we assumed that the Air Force will operate these simulators. Although the current trend is towards contractor operation, we were unable to acquire detailed information necessary to analyze costs of such operation. However, by assuming Air Force operation we probably provide an upper bound on costs if simulators are operated by contractors. Contractors tend to incur smaller costs because they do not have to rotate personnel every several years and because they can expedite the repair and supply processes when they encounter difficult support problems. Since the C-17 will probably be in the inventory for roughly a quarter of a century, we assumed a 25-year life cycle. Finally, we assumed that simulators will be utilized, in accordance with current Military Airlift Command practice, five days a week, sixteen hours a day.

[1]For a detailed description of our assessment of fiscal costs, see App. I in N-2301-AF.

[2]This is consistent with the U.S. Air Force Airlift Master Plan.

Table 3.1 summarizes the 25-year total system cost for the eight simulators. The incremental cost of including two g-seats per simulator (one for the pilot and one for the copilot) is $9.6 million more than the cost of simulators with no motion, and the incremental cost of including a motion platform is $24.1 million more than the cost of simulators with no motion. This $24.1 million represents only a 4 percent increase in the 25-year system cost of the no-motion alternative.

The incremental cost for *facilities* is surprisingly small. Three of the eight simulators would replace the three C-141 simulators currently at Altus. Since a new facility is presently under construction at Altus to receive C-141 simulators that could have six-dof motion platforms, there is no marginal facility cost incurred by replacing these simulators with C-17 simulators having motion platforms. The total incremental cost for facilities, as a consequence, results from the five other simulators.[3]

Two-thirds of the $24.1 million incremental cost for the motion platform alternative involves *25 years of operation and support*. This cost estimate may prove high if the Air Force elects to go with contractor-operated training facilities such as are now planned for the C-5 and as are already in place for the KC-10.

One of the surprising outcomes of the cost analysis was that only about 6 percent of *acquisition* costs (R&D and procurement) can be attributed to the motion platform system (see Fig. 3.1). Two-thirds of this 6 percent is due to direct costs of the motion system hardware,

Table 3.1

25-YEAR SYSTEM COSTS OF EIGHT FLIGHT SIMULATORS
(In $ million FY85)

Cost Category	No Motion Cost	G-Seat Cost	G-Seat Incremental Cost	Motion Platform Cost	Motion Platform Incremental Cost
Facilities	6.5	6.5	(0)	7.1	(0.6)
25-year O&S	455.6	461.4	(5.8)	472.3	(16.7)
Acquisition	120.9	124.7	(3.8)	127.7	(6.8)
Total system	583.0	592.6	(9.6)	607.1	(24.1)

[3]The incremental cost of building a facility to house a motion platform simulator is only $140,000 more than the cost of building a facility that does not have to house one.

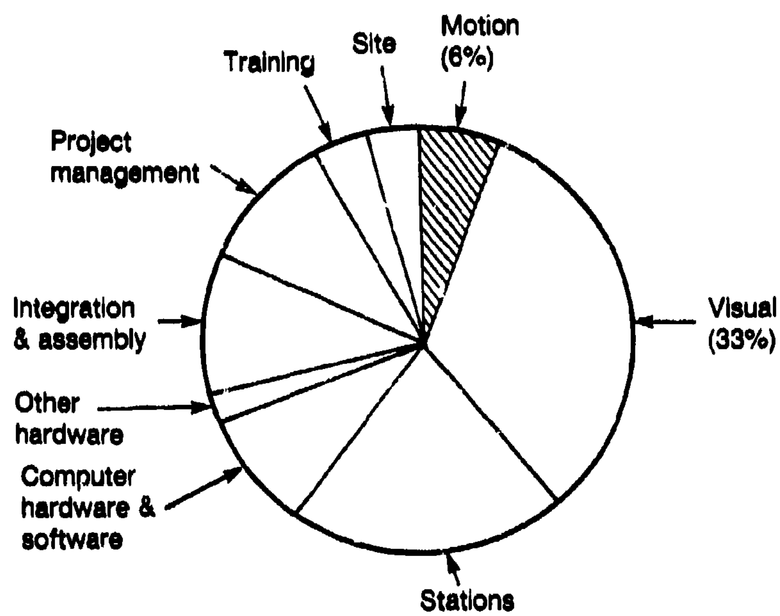

Fig. 3.1--Distribution of acquisition costs for flight simulators with motion platforms

computer software, etc. The other third is indirect costs extracted from the project management, integration and assembly, etc., categories depicted in Fig. 3.1. The 6 percent, therefore, represents the true marginal cost that would be incurred or avoided depending upon whether the motion platform were included or excluded.[4]

The acquisition cost of visual equipment for the C-17 simulator will be more than five times that of a motion platform. Indeed, visual equipment may cost considerably more than estimated here, since we have assumed that the C-17 visual system will be no more sophisticated than the one in the C-130 Weapon System Trainer currently at

[4]The 33 percent increment for the visual system depicted in Fig. 3.1 is, however, exclusively the *direct cost* for the visual system hardware, computer software, and the like. If the visual system had been the subject of our inquiry, we would have identified appropriate portions of the project management, integration and assembly, etc., categories that would be sensitive to the inclusion or exclusion of the visual system. *Thus the relative acquisition cost of the visual system versus the motion system is undoubtedly greater than the ratio of 33 percent to 6 percent.*

Little Rock. Requirements for low-level flight training, such as flying terrain-masking profiles to avoid enemy defenses, may create a need for more sophisticated visual equipment and hence lead to a more expensive C-17 simulator.

We can therefore conclude with a high degree of confidence that the inclusion of a platform motion system in the C-17 simulators would represent not more than 4 percent of the total 25-year system cost for the simulator, and would constitute a cost less than one-fifth that of the visual system.

Sensitivity Analysis

If one simulator has less training capability than another, it might be used less or procured in smaller quantities because the operator finds it less useful for training.[5] In such a situation, the operator would strive to shift some training to the aircraft, although—as we have indicated—certain tasks cannot be shifted to the aircraft for reasons of prudence or difficulty. Such a reduction in simulator utilization or procurement could also influence training-cost differences[6] among simulator alternatives.

Although we lacked sufficient information to estimate how demand for a C-17 simulator might change with changes in training capability, we parametrically estimated how costs would change if some training shifted from the simulator to the aircraft. Such shifting drives up the training costs of the no-motion and g-seat alternatives because aircraft marginal operating costs are more than eight times those for simulators.[7] For these less capable alternatives, savings from reduced utilization—or even from reduced procurement—are easily overwhelmed by the added training costs whenever slightly more than 1 percent of the simulator hours shift to the aircraft.[8]

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[5]Alternatively, the Air Force could attempt the same training with less capable simulators or it could concentrate on more repetitive training for those tasks the simulator could adequately train. But this approach might lead to such unquantifiable risks as not having fully trained crews for a wartime contingency, or losing an $80 million aircraft, its crew, and its cargo in peacetime because the quality and diversity of motion cues experienced by crew members in simulator training did not equip them to respond properly to the cues experienced in an actual in-flight emergency.

[6]Until now, our discussion of fiscal cost has considered only simulator costs for training; we neglected aircraft costs for training because they were constant for different simulator alternatives. In our sensitivity analysis, however, our discussion of fiscal cost considers "training costs," which include aircraft as well as simulator costs to reflect their tradeoffs.

[7]Greater aircraft use for training would also increase aircraft exposure to accidents and consume the useful life of the force more quickly.

[8]Even under the extremely optimistic assumption that as much training can be accomplished in one aircraft-hour as in one simulator-hour, an additional training cost of about $21 million is incurred over 25 years for each 1 percent reduction in simulator

In addition, some tasks and task variations not trainable in a low-capability simulator cannot be shifted to the aircraft. While we cannot estimate the actual opportunity cost of not training these tasks, the lower bound of this cost would correspond to the aircraft's marginal operating cost. The Air Force should be willing to pay that much to train the task in the aircraft (if it were possible) rather than reduce training standards by failing to train the task.

This lower bound on opportunity cost is larger than the corresponding net cost of shifting training to the aircraft. Because more than 40 percent of the tasks and task variations considered cannot be trained at all without the motion platform alternative, this suggests that the extra $24 million for the motion platform alternative almost certainly would be less expensive than the sum of the operating cost for additional training in the aircraft and the opportunity cost of those tasks that could not be trained.

Finally, if more than eight simulators are ultimately needed to satisfy the training demand, this is even more favorable for the motion platform alternative. It can satisfy the additional training demand relatively inexpensively with more simulators, while the lower-capability alternatives incur much higher training costs because of the need to use the aircraft much more and the inability either in the aircraft or in the simulator to train almost half the tasks and task variations considered.

These results suggest that changes in our assumptions concerning utilization and number of simulators merely enhance the attractiveness of the motion platform alternative.

AVAILABILITY OF SIMULATOR

Loss of simulator availability due to maintenance on the motion system concerns decisionmakers especially because of the Air Force's past experience with motion platforms.

This cost seems to have been greatest during the 1970s, when the current style of six-dof motion platform was first introduced. The initial model posed availability problems. Subsequent models have largely solved these problems by changing to a hydrostatic bearing design. By lowering friction, reducing pressures, and altering seals, the new design

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training hours that shift to the aircraft. Because of the almost four-to-one dominance of simulator operating costs over procurement costs, the results change only slightly if fewer simulators are procured to reflect hypothetically lower use.

ensures less wear and fewer leaks and thus has led to excellent availability rates.[9]

To examine the effect of platform motion systems on overall training availability of simulators, we asked four organizations to provide data on their recent experiences:

- United Airlines Aircrew Training Corporation
- Boeing Commercial Training Division of the Boeing Commercial Airplane Company
- American Airlines Training Corporation Training Center at Barksdale Air Force Base
- The 314th Tactical Airlift Wing at Little Rock Air Force Base.

United Airlines reported that its six-dof motion platforms, which have been in service for about five years, were each unavailable for an average of 86 hours per year because of maintenance on the motion platform (see Table 3.2). Filter changes and monthly preventive checks in most cases are performed during the third shift, when the simulator is not scheduled for training. That leaves an average of 42 hours per year per simulator during which maintenance on the motion system might decrease the availability of the simulator for training, and this is only 1 percent of the total annual training schedule.[10]

Table 3.2

PLATFORM AVAILABILITY:
UNITED AIRLINES AIRCREW TRAINING

Maintenance for Motion System	Average Unavailable Hours per Year per Simulator
Filter changes	8
Monthly preventative checks	36
Monthly interrupts	24
Pump/motor repair	6
Other downtime	12
Total	86

SOURCE: Data provided by United Airlines Aircrew Training Corporation, February 1985.

[9]The use of better drive algorithms and more computing power has complemented improvements in bearing design to also diminish problems created by poorly synchronized and false cues.

[10]Since these systems train commercial airline pilots, they must be maintained according to FAA specifications and they are subject to random FAA inspections. It is

Boeing reports that their simulators with modern hydrostatic motion platforms are available more than 99 percent of scheduled training time (16 hours a day, five to six days a week). Their preventive maintenance for motion platforms primarily involves changing hydraulic fluid and filters.

Likewise, American Airlines reports little difficulty maintaining the motion platforms for its two KC-10 simulators at Barksdale Air Force Base. During fiscal year 1984, they reported only two problems with the motion system,[11] which together consumed only nine hours (see Table 3.3).

The preceding simulators were operated and maintained by commercial organizations. Figure 3.2 shows the annual breakdown of simulator status for the C-130 simulators at Little Rock Air Force Base. This figure shows that the simulators were not available for use 12 percent of the time. Thus, no more than 12 percent of the time could have been lost due to maintenance, and maintenance personnel report that the motion system accounts for a very small portion of total maintenance time.

These data suggest that motion platforms no longer pose availability problems for simulators. While we have very little data on the avail-

Table 3.3

SIMULATOR AVAILABILITY AND UTILIZATION:
TWO KC-10 SIMULATORS AT BARKSDALE
AIR FORCE BASE
(FY 1984)

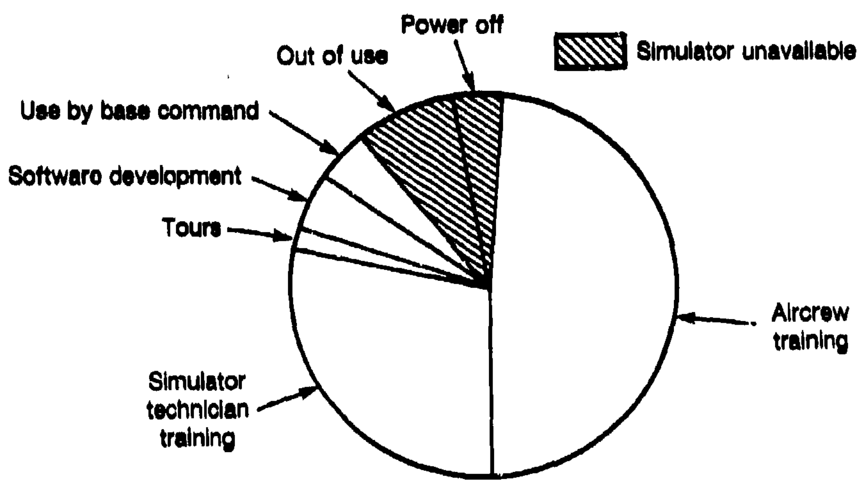
Training hours scheduled	5033
Training hours completed	4973
Total training hours lost	60
Hours lost due to motion system	9
Hours lost due to other unscheduled maintenance and mishaps	51

SOURCE: Data provided by American Airlines Training Corporation, February 1985.

doubtful, therefore, that much training occurs when the motion system operates improperly.

[11]One problem was with the motion bus printed circuit board and the other was with the motion controller cable.

ability of the g-seat considered in this analysis, we see no reason to believe that it would pose serious availability problems.[12]



SOURCE: Data provided by the 314th Tactical Airlift Wing at Little Rock AFB.

Fig. 3.2—C-130 simulator availability and utilization at Little Rock AFB

SUMMARY OF COSTS

Because differences in the availability of the three motion system alternatives are minor at best, the fiscal costs shown in Table 3.4 are the greatest cost consideration when differentiating among the alternatives. The motion platform alternative has the largest incremental 25-year system costs; however, it also has the lowest risk of incurring additional training costs. Shortcomings in the training capability of the competing alternatives could lead to opportunity costs and additional aircraft operating costs for training that easily overshadow the incremental cost of the motion platforms.

[12]Discussions with Air Force personnel indicate that training typically goes on regardless of whether g-seats are functioning. Hence, availability data for simulators with g-seats are not reliable indicators of g-seat dependability. We found some anecdotal evidence of problems with leaking pneumatic bladders and water condensation in g-seats, but in general personnel indicated g-seats do not present significant maintenance problems.

Table 3.4

SUMMARY OF ALL COSTS

Cost Measure	Alternative Case: No Motion	Alternative Case: G-Seat	Alternative Case: Motion Platform
Incremental 25-year system costs (In $ million FY 1985)	0	10	[illegible]
Risk of incurring additional training costs			
Contribution to unavailability of simulator	None	Small	Small

Rankings: Best Intermediate Worst

IV. CONCLUSIONS

Table 4.1 summarizes the assessed benefits and costs for the three simulator alternatives. Subject to our stringent criteria of what constitutes a trainable task, the motion platform enjoys a large advantage over other alternatives in terms of the number of trainable tasks and task variations. It also enjoys an advantage in terms of safety benefits,

Table 4.1

SUMMARY OF BENEFITS AND COSTS

Measure	Alternative Case: No Motion	Alternative Case: G-Seat	Alternative Case: Motion Platform
BENEFITS			
Subjective considerations			
Crew confidence			
Instructor confidence			
Training efficiency			
Contribution to safety			
Avoidance of simulator sickness			
Simulator training capability			
Tasks and variations trainable in the simulator	[illegible]	35%	100%
Tasks and variations requiring training in the aircraft	[illegible]	25%	0%
Tasks and variations not trainable at all	[illegible]	40%	0%
COSTS			
Incremental 25-year system costs (In $ million FY 1985)	0	10	[illegible]
Risk of incurring additional training costs			
Contribution to unavailability of simulator	None	Small	Small

Rankings: Best Intermediate Worst

subjective considerations such as crew and instructor confidence and training efficiency, and reductions in simulator sickness. Besides a very small contribution to simulator unavailability, the only negative feature of the motion platform would be the $24 million extra cost to procure and operate eight simulators. However, based on our sensitivity analysis, this cost would almost certainly be smaller than the increased training cost that would result from using a less capable simulator. This increased training cost is the sum of the operating cost for additional training in the aircraft and the opportunity cost of those tasks that could not be trained.

These findings assume that the Air Force maintains the general training standard implicit in our definition of trainable task. If the Air Force chose to train to a lower standard, this would reduce the advantages of the motion platform. But it would also cause the unquantifiable risks from training to a lower standard to become central to decisions involving the simulator alternatives. Such risks would include the possibility of not having fully trained crews for a wartime contingency or the possibility of losing an $80 million aircraft, its crew, and its cargo in peacetime because the simulator training experience did not equip the crew to respond properly to the cues experienced in an actual in-flight emergency.

Concerning benefits, we found that in terms of tasks trainable in the simulator, the motion platform alternative can train about five times more tasks and variations of tasks than the no-motion alternative, and about three times as many as the g-seat alternative. Moreover, with the g-seat and no-motion alternatives, a substantial fraction of the tasks can be trained only in the aircraft (one-quarter to one-third) or not at all (four-tenths to one-half). Thus because of their limited capabilities, the no-motion and g-seat alternatives would impose heavy wartime mission training demands on the C-17 aircraft that would be difficult to satisfy because of heavy peacetime airlift mission demands. By contrast, the motion platform alternative would allow pilots to use the simulator—rather than the heavily burdened airplane—to develop and maintain the skills, knowledge, and confidence required to successfully execute the wartime portion of the C-17 mission.

Concerning costs, we found that the incremental cost of motion platforms for eight simulators over a 25-year life cycle would be $24 million. This would help train aircrews for 208 PAA C-17s. Thus the costs of the motion platforms average $115,000 per aircraft per 25-year period—or $4,600 per aircraft per year. Is it worth $4,600 per year to have more qualified crews operating an $80 million aircraft? We think the answer is yes, especially since there will be five crews per airplane. Indeed, because of training capability shortcomings, the no-motion and

g-seat alternatives carry the risk of incurring opportunity costs and additional aircraft operating costs for training that could easily exceed the incremental cost of the motion platforms.

The attractiveness of the motion platform alternative is predicated, however, on the assumption that C-17 simulators will provide accurate motion cues and accurate visual cues. Accurate motion cues can only occur if special data are collected during the flight-test program. This is a major concern, since at the time of this study such data had not been included in the program plan and finalization of that plan is about to occur.

Even though we have placed great emphasis on the C-17's combat mission—which would not be shared by other aircraft—we believe the framework of our analysis should be generally applicable to other *large, multiengine transport aircraft* if it is adapted to their special situations and needs.

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